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Nitrogen and Phosphorus Status of Soils and Trophic State of Lakes Associated with Forage-Based Beef Cattle Operations in Florida

G. C. Sigua,* M. J. Williams, S. W. Coleman, and R. Starks

ABSTRACT

Forage-based livestock systems have been implicated as major contributors to deteriorating water quality, particularly for phosphorus (P) from commercial fertilizers and manures affecting surface and ground water quality. Little information exists regarding possible magnitudes of nutrient losses from pastures that are managed for both grazing and hay production and how these might impact adjacent bodies of water. We examined the changes that have occurred in soil fertility levels of rhizoma peanut (*Arachis glabrata* Benth.)-based beef cattle pastures ($n = 4$) in Florida from 1988 to 2002. These pastures were managed for grazing in spring followed by haying in late summer and were fertilized annually with P (39 kg P_2O_5 ha^{-1}) and K (68 kg K_2O ha^{-1}). Additionally, we investigated trends in water quality parameters and trophic state index (TSI) of lakes ($n = 3$) associated with beef cattle operations from 1993 to 2002. Overall, there was no spatial or temporal buildup of soil P and other crop nutrients despite the annual application of fertilizers and daily in-field loading of animal waste. In fact, soil fertility levels showed a declining trend for crop nutrient levels, especially soil P ($y = 146.57 - 8.14 \times$ year; $r^2 = 0.75$), even though the fields had a history of P fertilization and the cattle were rotated into the legume fields. Our results indicate that when nutrients are not applied in excess, cow-calf systems are slight exporters of P, K, Ca, and Mg through removal of cut hay. Water quality in lakes associated with cattle production was "good" (30–46 TSI) based on the Florida Water Quality Standard. These findings indicate that properly managed livestock operations may not be major contributors to excess loads of nutrients (especially P) in surface water.

In Florida, there are approximately 4.5 million ha of grazing lands. Florida's beef production ranks 11th among beef producing states in the United States and fourth nationally among states in number of herds with more than 500 brood cows. Florida has four of the nation's 15 largest ranches, the largest of these four has more than 35 000 brood cows on more than 121 406 ha (Florida Department of Agriculture and Consumer Services, 2004).

In the southeastern United States, particularly Florida, grazing areas have considerable variability in soils, climate, and growing season, which affects both types of forage that can be grown and overall environmental and biodiversity management. In Florida, most of the grazing areas are located in South Florida on flatwood soils. Flatwood soils comprise about 81 million km^2 or about 51% of Florida soils and are dominated by forestry, beef cattle, citrus, vegetable, and dairy operations (Botcher et al., 1998). The dominant soils are aquouds, aquents, and aquepts. They have hyperthermia temperature regimes and an aquic moisture regime. Because the land is flat and poorly drained, most of the runoff occurs when the water table is close to the surface during the rainy season, June to October. During that time, runoff can be high in the area because the soils are sandy spodosols, which have low nutrient retention capacity, especially P, and high P losses can occur (Botcher et al., 1998). Beef cattle operations have been suggested as one of the major sources of nonpoint-source P and N pollution that are contributing to the degradation of water quality in lakes, reservoirs, rivers, and ground water aquifers in Florida (Allen et al., 1976, 1982; Bogges et al., 1995; Edwards et al., 2000). Cattle manure contains appreciable amounts of N and P (0.6 and 0.2%, respectively), and portions of these components can be transported into receiving waters during severe rainstorms (Khaleel et al., 1980).

Work in other regions of the country has shown that when grazing animals become concentrated near water bodies, or when they have unrestricted long-term access to streams for watering, sediment and nutrient loading can be high (Thurow, 1991; Brooks et al., 1997). Additionally, there is a heightened likelihood of N and P losses from overfertilized pastures through surface water runoff or percolation past the root zone (Schmidt and Sturgul, 1989; Gburek and Sharpley, 1998; Stout et al., 2000).

Relatively little information exists regarding possible magnitudes of nutrient losses from grazed pastures in subtropical Florida. Sigua et al. (2004) found that the levels of soil P varied widely with different pasture management. The soil P levels of pastures with rhizoma peanuts that were grazed in spring and hayed in early fall were higher than bahiagrass (*Paspalum notatum* Flugge) pastures that were grazed all year long. The soil test value of P in grazed bahiagrass was about 23% higher than that of grazed and hayed bahiagrass, suggesting that grazing followed by haying could have lowered the level of soil P. In another study in southern Florida, Arthington et al. (2003) reported that the presence of beef cattle at three stocking rates (1.5, 2.6, and 3.5 ha per cow) had no impact on nutrient loads (P and N) in surface runoff water compared with pastures containing no cattle. However, these studies should not be considered as definitive for the region because of the

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Abbreviations: DSSP, degree of soil saturation with phosphorus; RP, rhizoma peanuts; STARS, Subtropical Agricultural Research Station; TN, total nitrogen; TP, total phosphorus; TSI, trophic state index.

wide range in management systems (fertilization, stocking rate, grazing system, forage type, etc.) that are used in beef cattle production in Florida systems.

Reduction of P transport to receiving water bodies has been the primary focus of several studies because P has been found to be the limiting nutrient for eutrophication in many Florida aquatic systems (Botcher et al., 1998; Sigua et al., 2000; Sigua and Steward, 2000; Sigua and Tweedale, 2003). Whether or not nutrient losses from grazed pastures are significantly greater than background losses and how these losses are affected by soil, forage management, or stocking density are not well defined (Gary et al., 1983; Edwards et al., 2000; Sigua et al., 2004).

Better understanding of soil P dynamics and other crop nutrient changes resulting from different management systems should allow us to better predict potential impact on adjacent surface waters. These issues are critical and of increasing importance among environmentalists, ranchers, and public officials in the state. We hypothesized that properly managed livestock operations would not be major contributors to excess loads of P and other crop nutrients in surface water. To verify our hypothesis, we examined the levels of nutrients in water and soils that are associated with forage-based pastures in subtropical Florida. The objectives of the study were to (i) assess the changes that have occurred in soil fertility levels in beef cattle pastures with rhizoma peanuts over a 15-yr period (1988–2002) and (ii) examine the levels of nutrients in water and assess the trophic state of lakes associated with beef cattle operations in central Florida from 1993 to 2002.

MATERIALS AND METHODS

Site Description

This study was conducted at the Main Station Unit (28.60–28.63° N, 82.36–82.38° W) of the Subtropical Agricultural Research Station (STARS) located 11 km north of Brooksville, FL (Fig. 1). The station has three major pasture units with a combined total area of about 1538 ha with 1295 ha in permanent pastures. Cattle used for nutritional, reproductive, and genetic research on the station include about 500 head of breeding females with a total inventory of about 1000 head

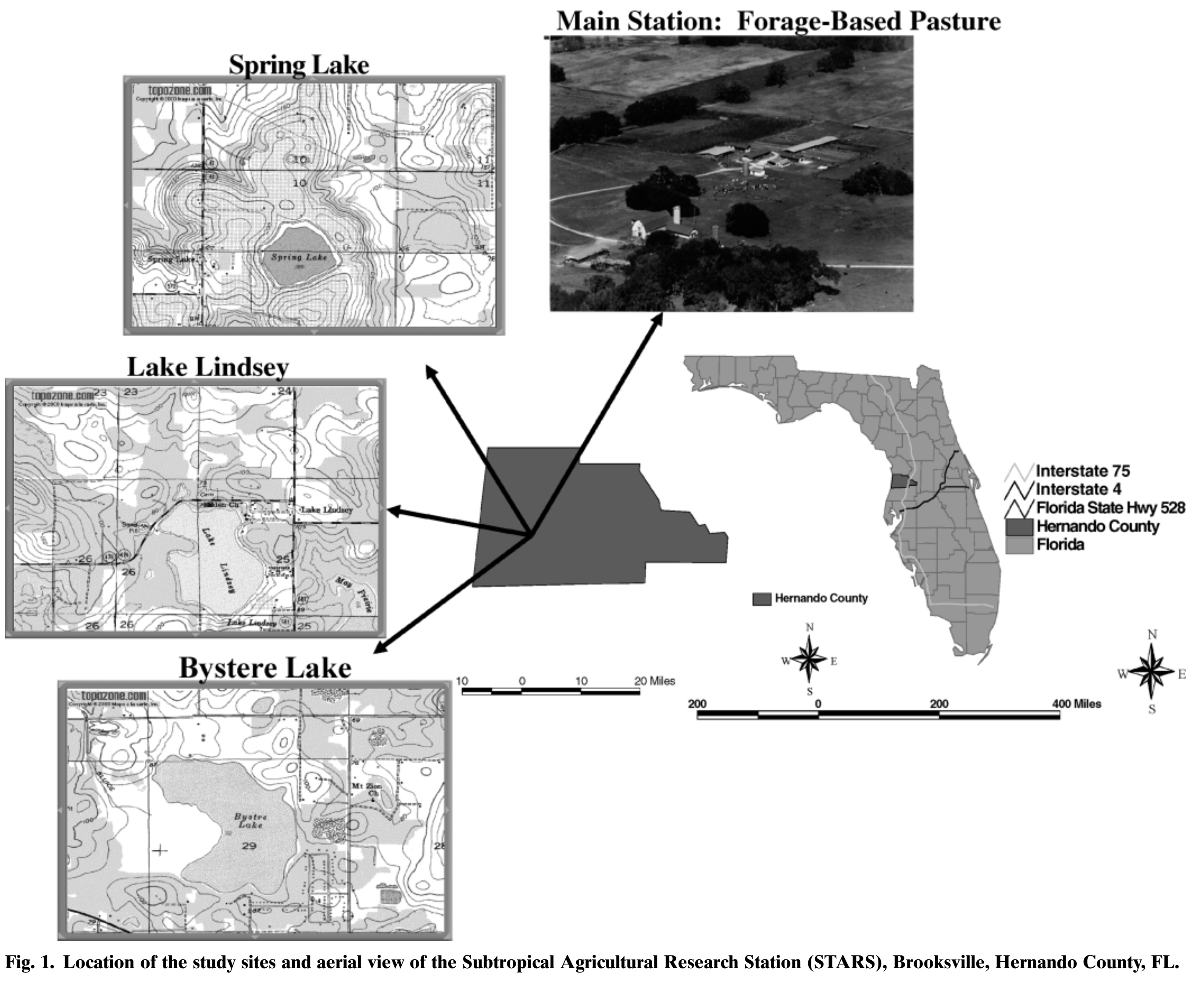


Fig. 1. Location of the study sites and aerial view of the Subtropical Agricultural Research Station (STARS), Brooksville, Hernando County, FL.

Table 1. Selected properties of surface soil (0–25 cm) averaged within respective beef pasture† fields of the Subtropical Agricultural Research Station (STARS), Brooksville, FL.

Property	Value (mean ± SD)
Texture, g kg^{-1}	
Sand	787.5 ± 37.5
Silt	162.5 ± 17.5
Clay	50.0 ± 5.5
pH in water	6.32 ± 0.06
Calcium, mg kg^{-1}	874.1 ± 271.2
Magnesium, mg kg^{-1}	93.4 ± 4.6
Potassium, mg kg^{-1}	63.4 ± 11.3
Soil organic C, g kg^{-1}	3.45 ± 0.06

† Nine subsamples (composite) were collected from four pasture fields.

of cows, calves, and bulls. The soil at the Main Station Unit is Flemington loamy sand (very-fine, smectitic, hyperthermic Typic Albaqualfs). Table 1 shows selected properties of surface (0–25 cm) soils in the pasture units of the study area. Forage production potential of the soils in the station is generally low to medium, with the main limitation being soil water availability.

The average annual (1983–2002) precipitation at the station was about 1262 mm with approximately half of this amount occurring during mid-June through mid-September. The lowest average temperature of 14°C occurs during January, but frosts are frequent during the winter months. The highest average temperature occurs during August although highs in the mid-30°C range occur regularly from May through September (Fig. 2).

Pasture Management

Cattle production at the station is forage-based with bahiagrass, the predominant forage species (approximately 1000 ha). Most of the bahiagrass pastures have been established for over 30 yr. The other major forage species (295 ha) is rhizoma peanuts (RP), a tropical legume with forage quality similar to alfalfa (*Medicago sativa* L.). Rhizoma peanut-based pastures are not

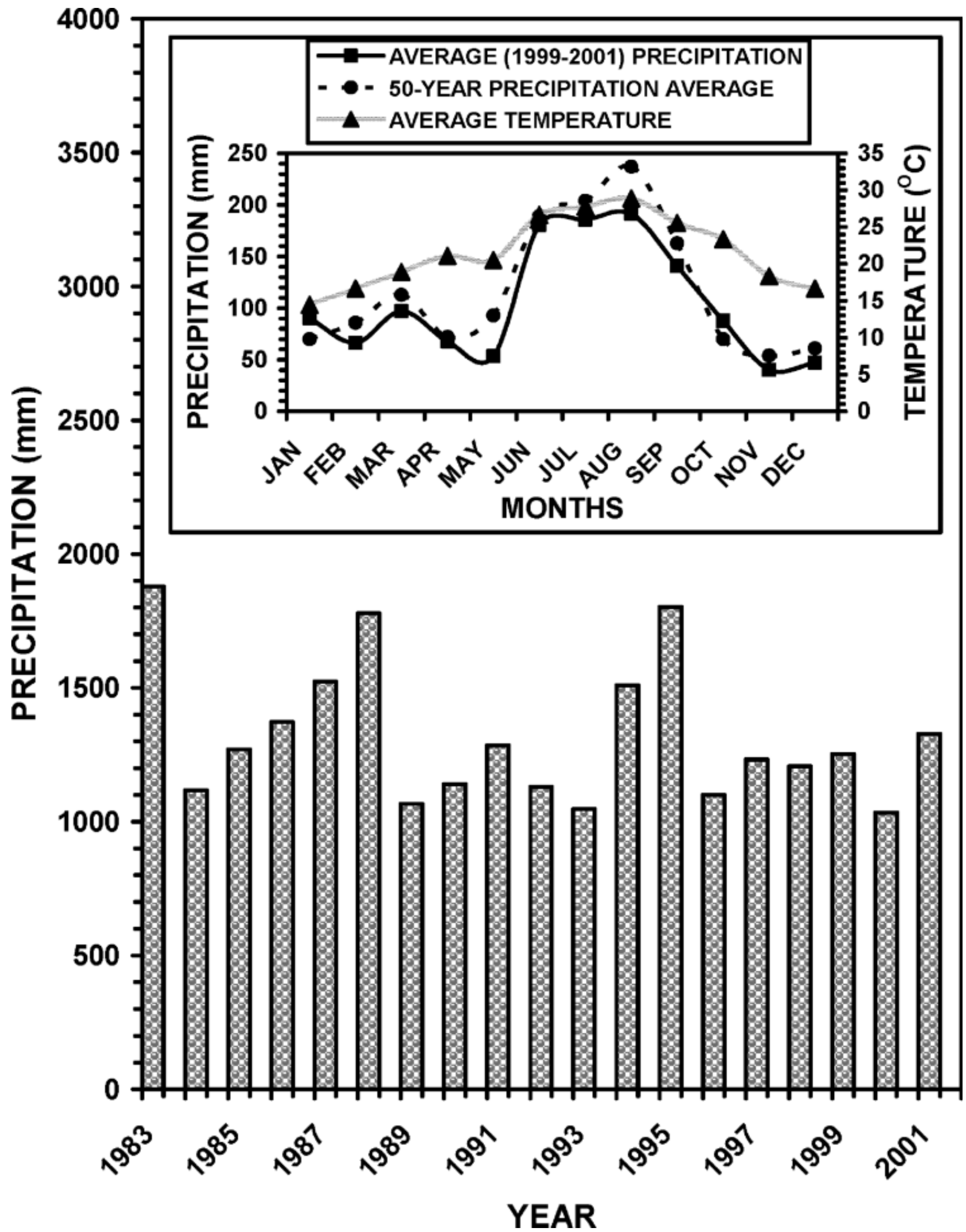


Fig. 2. Average monthly and annual rainfall and the 50-yr rainfall average, and average air temperature at Brooksville, FL.

pure stands, but are mixtures with bahiagrass and bermudagrass (*Cynodon dactylon* Pers.). Most of the RP stands were planted between 1980 and 1990. Pastures with RP did not receive N fertilization, but were fertilized annually with P (39 kg P_2O_5 ha^{-1}) and K (68 kg K_2O ha^{-1}) since establishment in 1988.

Rhizoma peanut-based pastures usually were managed for spring grazing until July followed by haying in late summer–early fall of each year. Historically, grazing cattle were rotated among pastures to allow rest periods of 2 to 4 wk based on herbage mass. The timing of movement for rotationally grazed cattle was determined by the herd manager's perception of forage availability based on plant height and not based on pasture measurement (Williams and Hammond, 1999). Starting in 2000, cattle were rotated on a 3-d grazing interval with 24 d of rest between pastures.

Soil Sampling and Soil Analyses

Soil samples were collected in the spring of 1988, 1997, 2000, and 2002 from RP-based pastures ($n = 4$) adjacent to Lake Lindsey (see water sampling section). Composite soil samples (nine subsamples) were collected using a steel bucket type auger (6.6-cm diameter) to a depth of 25 cm. In 2002, additional soil core samples were collected from the pastures ($n = 4$). Soil core samples were collected from the 0- to 25-, 25- to 50-, and 50- to 100-cm depths from each pasture using a hydraulic sinker drill (Concord Environmental Equipment, Hawley, MN). The additional depths of soil sampling were added in 2002 to assess and quantify vertical distribution of soil P and other crop nutrients.

Soil samples were air-dried and passed through a 2-mm mesh sieve before chemical extraction of soil P and other crop nutrients. Soil P, Ca, Mg, and K were extracted with double acid (0.012 M H_2SO_4 + 0.05 M HCl) as described by Mehlich (1953) and analyzed, using an inductive coupled spectrophotometer. Distilled water was added (1:2 on a gravimetric basis) to 10 g of air-dried soil and soil pH was determined with a glass electrode (McLean, 1982). The degree of soil saturation with phosphorus (DSSP) as described in Eq. [1] was computed using the P, Fe, and Al contents of the soil (Hooda et al., 2000):

$$\text{DSSP (\%)} = ([\text{P}] \times 100)/[\text{Fe} + \text{Al}] \qquad [1]$$

Lake Sites, Water Sampling, and Analysis

The lakes we studied were adjacent to or within about a 14-km radius from the USDA-ARS, Subtropical Agricultural Research Station, Brooksville, FL (Fig. 1). These lakes are associated with forage-based beef cattle operations. The lakes were (i) Lake Lindsey (28°37.76′ N, 82°21.98′ W), adjacent to STARS; (ii) Spring Lake (28°29.58′ N, 82°17.67′ W), about 10 km away from STARS; and (iii) Bystre Lake (28°32.62′ N, 82°19.57′ W), about 14 km away from STARS.

Lake Lindsey, which is a Type 3 lake (inflow–outflow) has a total surface area of 55 ha with average depth of 10 m, and is within the Withlacoochee River basin. The major land uses and land covers of Lake Lindsey within 500 m of lakeshore from 1990 to 2000 were: forest (39.7%), cropland and pastureland (34.3%), wetlands (13.1%), and urban (12.9%). Bystere Lake has a total surface area of 125 ha and is classified as a Type 3 lake (inflow–outflow) within the Withlacoochee River basin. The major land uses and land covers in Bystere Lake from 1990 to 2000 were: cropland and pastureland (49.4%), forest area (17.7%), wetlands (11.1%), and urban area (21.8%). Like Bystere Lake, Spring Lake is within the Withlacoochee River basin with average depth of 7 m. Spring Lake has a total surface area of about 24 ha and is classified as a Type 4 (isolated) lake. The major land uses and land covers of Spring Lake within 500 m of lakeshore from 1990 to 2000 were: cropland + pastureland (45.5%), forest lands (33.9%), wetlands (9.2%), and urban area (11.4%). Table 2 shows the major land uses and land covers within 500 m of lakeshore for Bystere Lake, Lake Lindsey, and Spring Lake for the years 1990, 1995, and 2000. Except for the slow-pace land use change of urban areas, it appears that there have not been any significant land use increases over the 10-yr span (Table 2).

Monthly water quality monitoring of lakes associated with beef cattle pastures was begun in 1993 and continued until 2002 by the field staff of the Southwest Florida Water Management District (SWFWMD). Monthly water samples were taken directly from the lakes using a water (Van Dorn) grab sampler. Water quality parameters monitored were Ca, Cl, NO_2 + NO_3–N, NH_4–N, total N, total P, K Mg, Na, Fe, and pH. All sampling, sample preservation and transport, and chain of custody procedures were performed in accordance with a USEPA-approved quality assurance plan with existing quality assurance requirements (USEPA, 1979; American Public Health Association, 1992). The SWFWMD Analytical Laboratory, using USEPA-approved analytical methods, performed the chemical analyses of water samples from the lakes (USEPA, 1979).

Trophic State Index Calculation

Lake trophic state index (TSI) is understood to be the biological response of a lake to forcing factors such as nutrient additions. Nutrients promote growth of microscopic plant cells (phytoplankton) that are fed on by microscopic animals (zooplankton). The TSI of Carlson (1983) uses algal biomass as the basis for trophic state classification (e.g., oligotrophic, mesotrophic, eutrophic, and hypereutrophic).

For our study, we used the Florida Trophic State Index of Brezonik (1984), which was derived using data from 313 Florida lakes. The first step involved in assigning a TSI value was to assess the current nutrient status based on the total nitrogen (TN) to total phosphorus (TP) ratio of the lake. The TN to TP ratios were classified into three categories: nitrogen limited (TN/TP < 10:1), phosphorus limited (TN/TP > 30:1), and balanced (10:1 ≤ TN/TP ≤ 30:1). The TSI of each lake that we studied was calculated by entering key water quality parameters: TP (μg L^{-1}), TN (mg L^{-1}), and chlorophyll *a* (CHL, mg m^{-3}) for the measurements of planktonic algae density, and Secchi depth (m) for measuring water transparency into an empirical formula (Eq. [2]–[4]). Equation [2] (P-limited) was used to calculate the TSI values for Lake Lindsey and Spring Lake while Eq. [3] (N-limited) was used

Table 2. Major land uses and land covers within 500 m of lakeshore for Bystre Lake, Lake Lindsey, and Spring Lake for the years 1990, 1995, and 2000.†

Lake	Year	Urban	Cropland + pastureland	Forest	Wetlands
		%			
Bystere Lake	1990	19.6	49.7	17.6	13.1
	1995	25.0	46.6	17.6	10.8
	2000	20.9	51.8	17.9	9.4
	average	21.8	49.4	17.7	11.1
Lake Lindsey	1990	8.5	37.8	39.0	14.7
	1995	14.5	31.4	38.6	15.5
	2000	15.6	33.7	41.5	9.2
	average	12.9	34.3	39.7	13.1
Spring Lake	1990	9.2	47.9	32.4	10.4
	1995	11.7	43.9	33.7	10.7
	2000	13.2	44.8	35.6	6.4
	average	11.4	45.5	33.9	9.2

† Source: Resources Data Section, Southwest Florida Water Management District, Tampa, FL.

to calculate the TSI value for Bystere Lake. A novel paper on trophic state index for lakes written by Carlson (1977) was an excellent reference to explain the mathematical derivations of the different equations listed below.

I. Phosphorus-limited lakes (TN/TP $>$ 30:1)

$$\mathrm{TSI\ (average)} = 1/3[\mathrm{TSI\ (CHL)} + \mathrm{TSI\ (Secchi\ depth)} + \mathrm{TSI\ (TP)}] \quad [2]$$

where:

$$\mathrm{TSI\ (CHL)} = 16.8 + 14.4 \times \ln(\mathrm{CHL}),\ (\mathrm{mgm^{-3}})$$
$$\mathrm{TSI\ (Secchi\ depth)} = 60.0 - 30.0 \times \ln(\mathrm{Secchi\ depth}),\ (\mathrm{m})$$
$$\mathrm{TSI\ (TP)} = -23.8 + 23.6 \times \ln(\mathrm{TP}),\ (\mu\mathrm{g\ L^{-1}})$$

II. Nitrogen-limited lakes (TN/TP $<$ 10:1)

$$\mathrm{TSI\ (average)} = 1/3[\mathrm{TSI\ (CHL)} + \mathrm{TSI\ (Secchi\ depth)} + \mathrm{TSI\ (TN)}] \quad [3]$$

where:

$$\mathrm{TSI\ (CHL)} = 16.8 + 14.4 \times \ln(\mathrm{CHL}),\ (\mathrm{mg\ m^{-3}})$$
$$\mathrm{TSI\ (Secchi\ depth)} = 60.0 - 30.0 \times \ln(\mathrm{Secchi\ depth}),\ (\mathrm{m})$$
$$\mathrm{TSI\ (TN)} = 59.6 + 21.5 \times \ln(\mathrm{TN}),\ (\mu\mathrm{g\ L^{-1}})$$

III. Nutrient-balanced lakes (10:1 $\leq$ TN/TP $\leq$ 30:1)

$$\mathrm{TSI\ (average)} = 1/3\{\mathrm{TSI\ (CHL)} + \mathrm{TSI\ (Secchi\ depth)} + [0.5\mathrm{TSI\ (TP)} + \mathrm{TSI\ (TN)}]\} \quad [4]$$

where:

$$\mathrm{TSI\ (CHL)} = 16.8 + 14.4 \times \ln(\mathrm{CHL}),\ (\mathrm{mg\ m^{-3}})$$
$$\mathrm{TSI\ (TN)} = 56 + 19.8 \times \ln(\mathrm{TN}),\ (\mu\mathrm{g\ L^{-1}})$$
$$\mathrm{TSI\ (TP)} = -18.4 + 18.6 \times \ln(\mathrm{TP}),\ (\mu\mathrm{g\ L^{-1}})$$
$$\mathrm{TSI\ (Secchi\ depth)} = 60.0 - 30.0 \times \ln(\mathrm{Secchi\ depth}),\ (\mathrm{m})$$

Data Reduction and Data Analysis

The levels and temporal changes of soil P and other crop nutrients (0–25 cm depth only) in RP-based pastures (n = 4) from 1988 to 2002 were analyzed using the repeated measures (PROC MIXED) of variance procedures (SAS Institute, 2000). Where the F test indicated a significant ($P \leq 0.05$) effect, means were separated according to Duncan's multiple range test at P = 0.05 (SAS Institute, 2000). Missing values were handled appropriately by following the procedures described in *SAS User's Guide: Basics* (SAS Institute, 1985).

Soil core data taken in 2002 for the pastures (n = 4) was analyzed separately because of the additional source of variability (i.e., soil depth, n = 3) on soil P and other crop nutrients. Data were analyzed following the analysis of variance procedures (PROC ANOVA) using the balanced split-plot design with pasture field as the main plot and soil depths (0–25, 25–50, and 50–100 cm) within each pasture field as the subplot. Where the F test indicated a significant ($P \leq 0.05$) effect, means were separated by calculation of least significant difference (SAS Institute, 2000).

The lake data (1993–2002) were used to analyze spatial (lakes) and temporal (year) variations in water quality of lakes associated with forage-based pasture using the PROC ANOVA procedures (SAS Institute, 2000). Spatial and temporal changes in water quality were analyzed using the balanced split-plot design with lakes as the main plot and year as the sub-plot. Additionally, data assessment and trend analysis in water quality for the forage-based lake system followed the stepwise regression procedures (Montgomery, 1984; Montgomery and Rechov, 1984). Results of parametric data analyses are reported in this paper.

RESULTS AND DISCUSSION

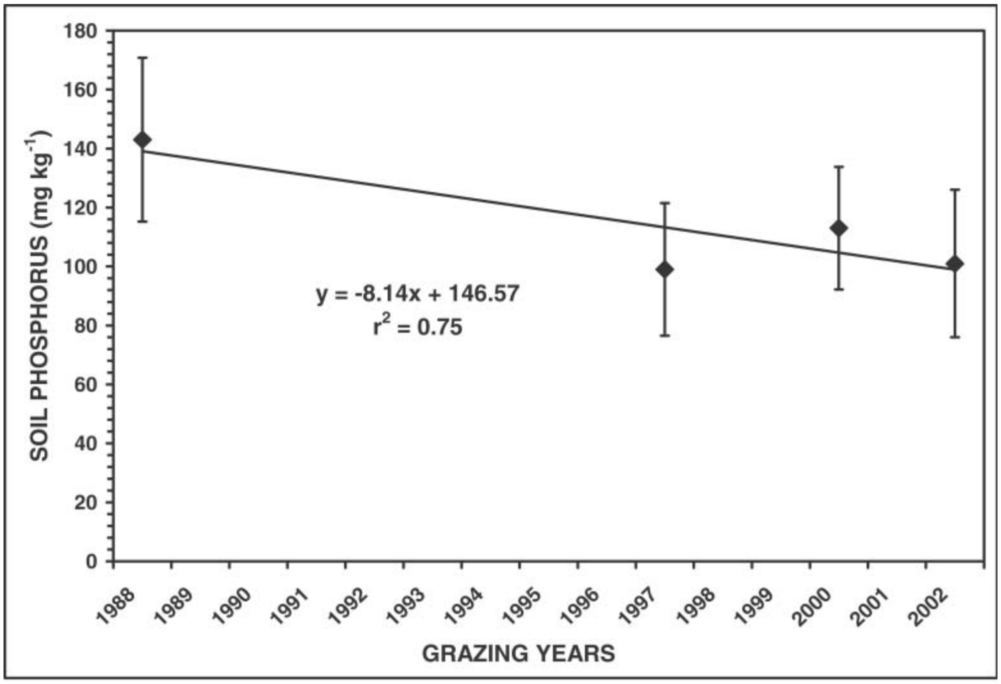
Levels and Changes of Soil Nutrients and Soil pH

The nutrient test values in pastures at STARS adjacent to Lake Lindsey declined from 1988 to 2002. Soil P level in 1988 was about 143 mg kg^{-1} compared with 101 mg kg^{-1} in 2002 (Fig. 3). The average K, Ca, and Mg levels in 1988 were 76, 1102, and 59 mg kg^{-1} compared with their levels in 2002 of 34, 487, and 33 mg kg^{-1}, respectively (Fig. 3 and 4). Soil pH in 1988 was 6.88 and 5.58 in 2002 (Fig. 5).

During the last 15 yr, soil test values for P, K, Ca, and Mg in RP-based pastures have declined by about 8.14, 6.79, 125.86, and 5.21 mg kg^{-1} yr^{-1}, respectively (Fig. 3 and 4). The regression models that best describe the changes and/or depletion rate of soil P, K, Ca, and Mg are also shown in Fig. 3 and 4. The regression model for soil pH is shown in Fig. 5. On the average, soil pH in pastures decreased by about 0.27 pH unit on annual basis. Declining levels of crop nutrients, especially soil P, can be attributed to the different pasture management being practiced in STARS. Our pasture fields with RP are being grazed in spring until July followed by haying of pastures in late summer and early fall. Soil P or other crop nutrients (K, Ca, or Mg) are not effectively removed from the forage system by grazing livestock. Nutrient removal is accomplished only by removing forage as hay crop and transporting the nutrient away from the application site. Haying of RP-based pastures removes biomass-containing nutrients, whereas grazing largely recycles nutrients (Sigua et al., 2004). Nutrients may enter the pasture system from a number of sources (e.g., fertilizers, manures, urine, crop residues, atmospheric) and could be loss via erosion, runoff, leaching to ground water, and haying (Fig. 6). Maintaining a balance between the amounts of nutrients removed as forages, hay, or livestock is critical for productive crop growth and water quality protection. If more nutrients are added than can be used for productive forage growth, nutrients will build up in soil, creating high risk for runoff and water contamination.

Effective use and cycling of nutrients is critical for pasture productivity and environmental stability. However, nutrient cycles (carbon, nitrogen, phosphorus, and sulfur) in pastures are complex and interrelated (Fig. 6). Each cycle has its complex set of interactions and transformations as well as interactions with the other cycles. Pasture management practices influence the interactions and transformations occurring within nutrient cycles.

Soil nutrient levels in 2002 did vary ($P < 0.05$) with soil depth (Table 3). As might be expected for all nutrients, including soil P and DSSP, their levels were higher in the 0- to 25-cm depth of the soil pedon than either the 25- to 50- or 50- to 100-cm depths. The level of soil P and DSSP in the 0- to 25- and 25- to 50-cm depths were higher than at the 50- to 100-cm soil depth. This suggests that there had been no movement of fertilizer P into the soil pedon since average DSSP in the upper



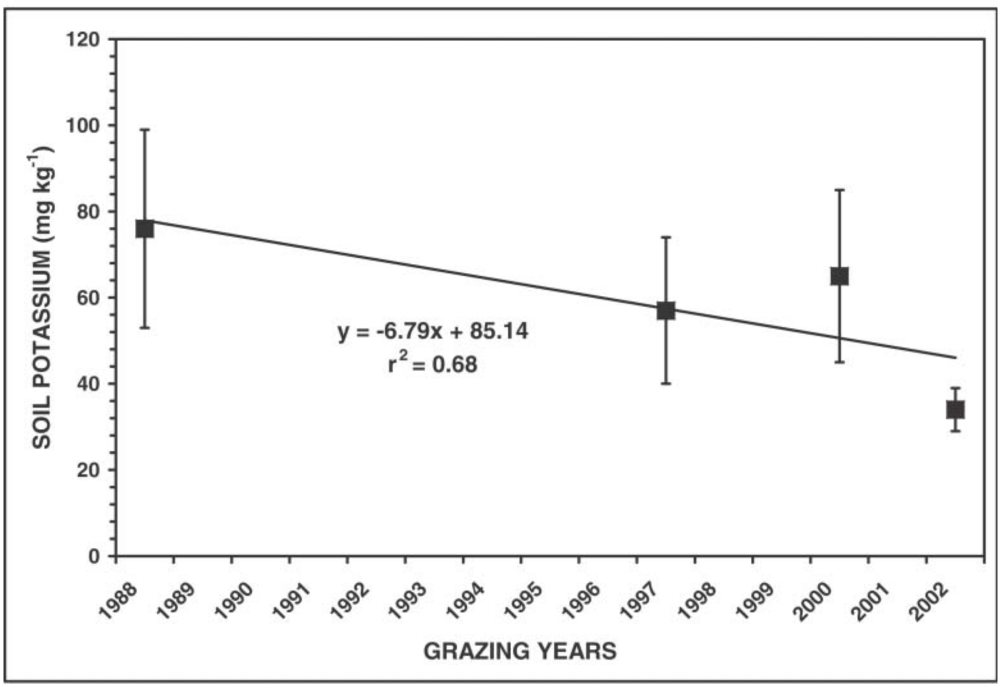
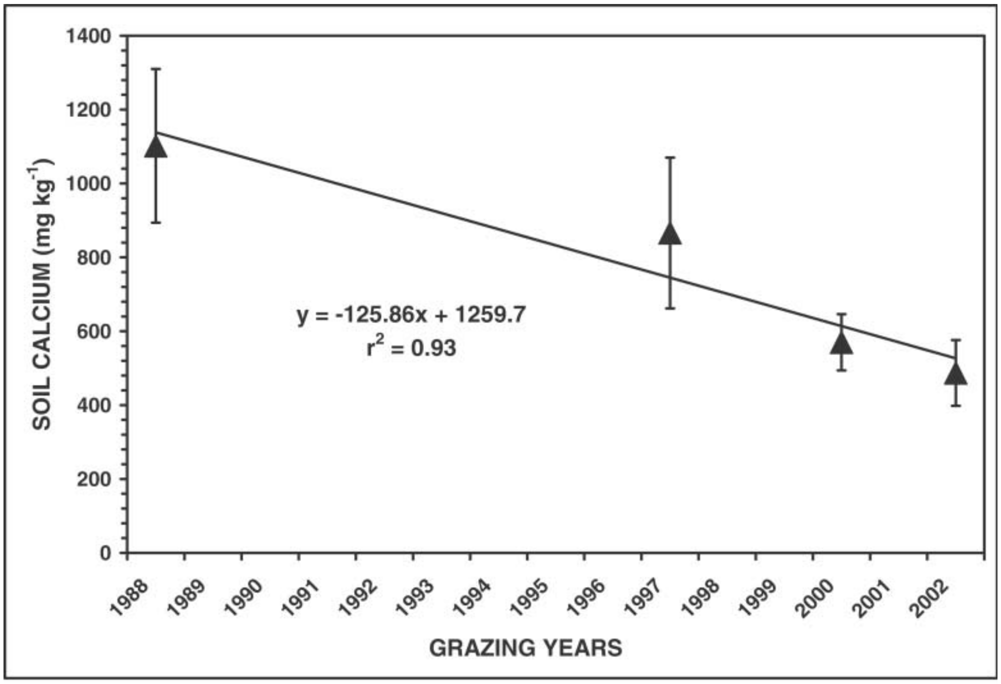


Fig. 3. Annual level (mean ± SD) and rate of decline for soil P and K in a forage-based beef cattle pasture system.

50 cm was 23% while DSSP at 50 to 100 cm was about 12% (Table 3). Hooda et al. (2000) reported that P desorbed was related to the degree to which the soils were saturated with P (DSSP), accounting for 94% of the variation for P desorbed. Using their regression model ($y = 1.14 + 0.59 \times$ DSSP; $r^2 = 0.96$), our study yielded an average P desorbed of 18.2, 19.6, and 7.3 mg P kg^{-1} soil at 0- to 25-, 25- to 50-, and 50- to 100-cm depths, respectively. Pote et al. (1996) reported a good correlation between the DSSP and dissolved reactive P in runoff from grass plots on a Captina silt loam. Several studies have found that DSSP needs to exceed 45 to 60% before dissolved reactive P becomes a problem (Heckrath et al., 1995; Hooda et al., 2000). Our results do not even approach this level of DSSP (Table 3), suggesting that dissolved reactive P is not a problem.

Concern for losses of soil P by overland flow were noted when soil P exceeded 150 mg kg^{-1} in the upper 20 cm of soil (Johnson and Eckert, 1995; Sharpley et al., 1996). This concentration of soil P should not be considered an absolute maximum number for soil P to have been harmful to water quality and the environment, but



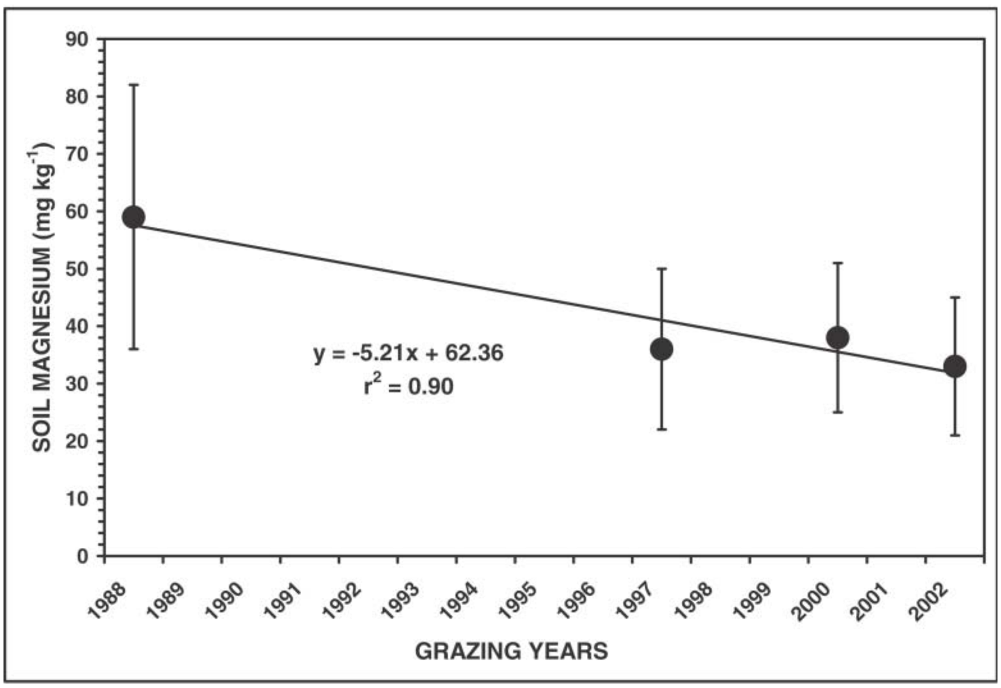


Fig. 4. Annual level (mean ± SD) and rate of decline for soil Ca and Mg in a forage-based beef cattle pasture system.

rather a good indicator of P accumulation in the soil. Thus, the average levels of soil P in this study, even those in 1988 (Fig. 3), are of little environmental concern. Sharpley (1997) noted that all soils do not contribute equally to P export from watersheds or have the same potential to transport P to runoff. In their studies, Coale and Olear (1996) observed that soil test P levels did not accurately predict total dissolved P. However, they noted that, in all cases studied, soil test P levels were significantly related to an increase in total dissolved P. Soil testing is currently the best management tool available to ensure that soils do not become overloaded with P, which increases the likelihood of their contribution to pollution in surface waters downstream (Norfleet et al., 1996).

Overall, there was no spatial or temporal buildup of soil P and other crop nutrients in RP-based beef cattle pastures. In fact, there was a decline in soil P and other crop nutrients even though the fields had a history of P fertilization and the cattle were rotated into the experimental fields from legume fields on the unit that still received regular applications of P. Our results

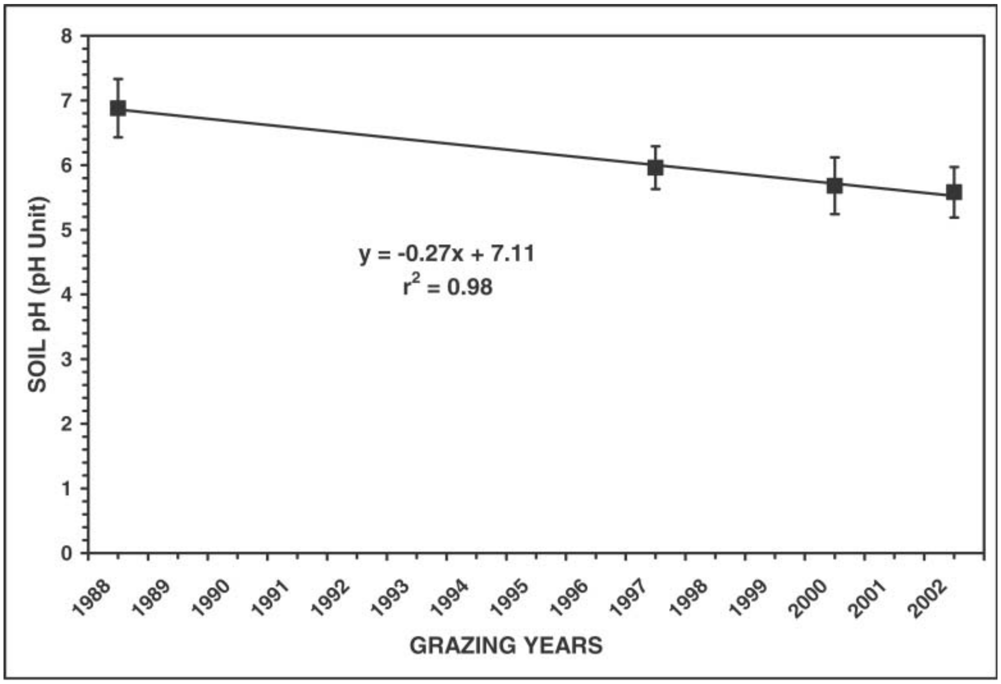


Fig. 5. Annual level (mean ± SD) and rate of decline for soil pH in a forage-based beef cattle pasture system.

indicate that when nutrients are not applied in excess, cow-calf systems are slight exporters of P, K, Ca, and Mg. Hence, properly managed livestock operations may not be major contributors to excess loads of P and other crop nutrients in surface water.

It is interesting to note that Ca is being lost more rapidly when compared with Mg (Fig. 4). The rate of Ca depletion in our study may be important because of the potential Ca deficiency to develop in soil. Barber (1964) reported that the Ca to Mg ratios can vary from 1 to 49 without affecting crop yield as long as the total amount of exchangeable Mg in the soil is not too low. The average level of Mg of 33 mg kg^{-1} in the upper 25 cm in 2002 (Table 3) is about borderline deficient for optimum bahiagrass growth (Chambliss and Kidder, 2003). They reported that Mg requirements of all forage crops normally should be satisfied when the value for Mehlich 1 (Mehlich, 1953) extractable Mg is at or above 30 mg kg^{-1}. Another interesting result of the pasture management was the decline in soil pH (Fig. 5) over the years, which may be a response to the declining Ca levels in the soil. The soils in the study area are dominated by sandy particles (787.5 ± 37.5 g kg^{-1}, Table 1). Soils have low buffering capacity and tend to become more acidic even before the levels of Ca become limiting as a plant nutrient. This may require application of dolomitic lime to

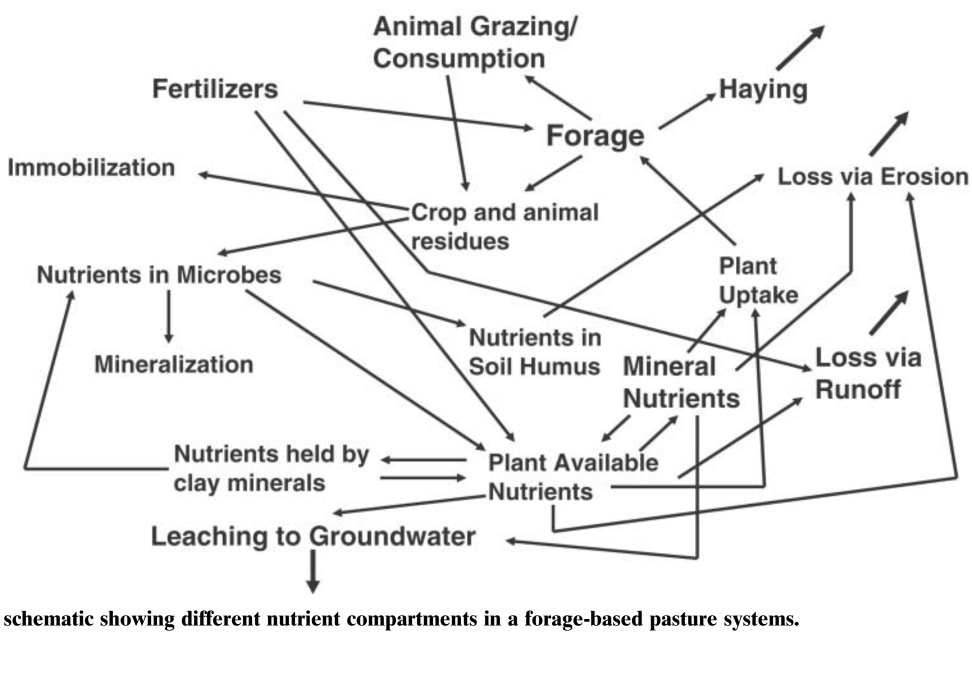


Fig. 6. Generalized schematic showing different nutrient compartments in a forage-based pasture systems.

Table 3. Mean levels of soil† P and other crop nutrients at different soil depths of subtropical pastures with forage-based beef cattle operations in 2002.

Soil depth	DSSP‡	Total P	Total N	Ca	Mg	pH
cm	%	mg kg^{-1}				
0–25	32.6 ± 4.0a§	113.3 ± 25.2a	0.61 ± 0.2a	570.0 ± 189.1a	33.4 ± 9.9a	5.57 ± 0.39a
25–50	22.3 ± 1.6b	67.1 ± 11.2b	0.73 ± 0.1a	314.0 ± 100.1b	13.9 ± 6.1b	5.68 ± 0.28a
50–100	12.3 ± 2.3c	18.4 ± 6.3c	0.29 ± 0.05b	174.9 ± 34.9b	11.1 ± 2.5b	5.96 ± 0.29a

† Soil samples were collected near Lake Lindsey.
‡ Degree of soil saturation with phosphorus.
§ Means in columns followed by common letter(s) are not significantly different from each other at $P \leq 0.05$.

correct the Ca and Mg deficiency as well as raise the pH (Tisdale and Nelson, 1980).

Status of Water Quality in Lakes

Assessment of water quality data from 1993 to 2002 confirms that water-quality variations (temporal and spatial) existed in lakes associated with beef cattle pasture systems in central Florida (Table 4). The lakes were found to differ from each other in Ca, $NO_2 + NO_3$–N, TN, TP, K, Mg, Na, and Fe. Significant temporal variations were observed for NH_4–N, TP, and Fe while significant interaction effects (lakes × year) were only noted for NH_4–N, TP, Mg, Na, and Fe (Table 4). Summary statistics (1993–2002) of selected water quality parameters in lakes associated with forage system are shown in Table 5.

The levels of $NO_2 + NO_3$–N and NH_4–N in lakes did not show any significant differences from 1993 to 2002 while TN of Bystere Lake declined from 1.12 to 0.76 mg L^{-1} between 1993 and 2002 (Table 6). Lake Lindsey's TN was about 0.82 mg L^{-1} in 1993 and 0.80 mg L^{-1} in 2002 while Spring Lake's TN was about 0.65 mg L^{-1} in 1993 and 0.78 mg L^{-1} in 2002. The levels of TP in Bystere Lake between 1993 and 2002 increased from 0.08 to 0.34 mg L^{-1} while levels of TP in Lake Lindsey did not change from 1993 to 2002. A decline of TP was noted in Spring Lake from 1993 (0.19 mg L^{-1}) to 2002 (0.01 mg L^{-1}). With the continuous conversion of cropland and pastureland to residential use (although at slow pace), contribution of nutrients from anthropogenic sources is becoming a big concern environmentally over time for lakes associated with forage-based pasture systems (Table 2). Concentrations of other selected water quality parameters between 1993 and 2002 in lakes associated with forage-based pasture ecosystem are shown in Table 6.

Total Nitrogen to Total Phosphorus Ratio

Nitrogen and P are the primary crop nutrients that can impact the environment. When applied in excess of crop needs, nutrients can run off into surface waters resulting in excessive aquatic plant growth and toxicity to certain fish species. The TN to TP ratio may be a useful method to establish the N and P reduction targets in the environment (Sigua et al., 2000). The ratio of TN to TP is one of the important components in calculating the TSI of lakes.

Several studies have shown that a TN to TP ratio of ≤10:1 appears to favor algal blooms, especially blue-green algae, which are capable of fixing atmospheric N (Sakamoto, 1966; Schindler, 1974; Chiandini and Vighi, 1974; Sigua et al., 2000). Figure 7 shows the TN to TP ratio of the lakes we studied which were associated with beef cattle operations. Lake Lindsey and Spring Lake can be classified as P-limited lakes with TN to TP ratios of 41:1 and 51:1, respectively. Bystere Lake with a TN to TP ratio of 9:1 was classified as a N-limited lake and may have higher probability for algal bloom compared with Lake Lindsey and Spring Lake because of its higher P levels. From 1993 to 2002, the TP in Bystere Lake increased from 0.08 to 0.34 mg L^{-1}.

Trophic State Index of Lakes

The Florida TSI was devised to integrate different but related measures of lake productivity or potential productivity, into a single number that ranges from 0 to 100. The measures included in the calculation of TSI are water transparency (Secchi depth), chlorophyll *a* (measurement of algae content), TN, and TP. The Florida TSI for Lake Lindsey, Spring Lake, and Bystre Lake were 35, 30, and 46, respectively (Fig. 8). Based on this, the TSI of these lakes can be classified as "good" according to Florida Water Quality Standard (TSI of 0 to 59 = "good", TSI of 60 to 69 = "fair", and TSI of 70 to 100 = "poor"). Although the TSI levels of the three lakes did not show any significant change from 1993 to 2002, TSI levels increased numerically for all lakes (Fig. 8). This is reflected in a change in the trophic status of Bystere Lake. Lake Lindsey with TSI of 31 and 38 in 1993 and

Table 4. Analysis of variance (*F* values) on the temporal and spatial distribution of selected water quality parameters of lakes associated with forage-based beef cattle operations.

Source of variation	Ca	$NO_2 + NO_3$–N	NH_4–N	Total N	Total P	K	Mg	Na	Fe
Among lakes	142.5***	5.96**	0.2NS	3.72*	10.7**	121.2***	319.5***	73.4***	6.9**
Among years	0.65NS	0.65NS	5.9*	0.4NS	3.6**	1.6NS	1.0NS	0.4NS	4.2**
Lakes × years	1.12NS	0.6NS	3.6**	0.2NS	4.4**	1.9NS	2.7*	2.4*	3.2**

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.

Table 5. Summary statistics of the levels of selected nutrients and water pH in lakes associated with forage-based beef cattle operations.

Nutrient	Mean	Median	SD	Minimum	Maximum	Skew
	mg L^{-1}					
			Bystere Lake			
Ca	33.86	35.00	6.47	22.00	46.00	0.10
Cl	8.97	9.00	1.39	5.50	11.0	−0.95
$NO_2 + NO_3$–N	0.01	0.01	0.00	0.01	0.01	–
NH_4–N	0.04	0.04	0.03	0.01	0.11	0.84
Total N	1.05	0.90	0.39	0.53	1.86	0.75
Total P	0.17	0.09	0.14	0.05	0.53	1.55
K	4.67	4.75	2.44	0.07	9.25	−0.09
Mg	2.82	2.75	0.68	2.00	3.90	0.61
Na	5.62	5.45	0.90	3.90	7.00	−0.31
Fe	0.12	0.11	0.07	0.033	0.27	0.56
pH	7.88	7.65	0.92	6.97	10.02	1.53
			Lake Lindsey			
Ca	6.09	5.00	3.88	2.59	17.00	2.13
Cl	5.65	5.00	3.00	3.50	16.00	3.31
$NO_2 + NO_3$–N	0.01	0.01	0.003	0.002	0.010	−3.87
NH_4–N	0.04	0.02	0.05	0.01	0.19	2.43
Total N	0.94	0.87	0.29	0.53	1.60	1.31
Total P	0.04	0.03	0.05	0.01	0.21	3.60
K	0.33	0.10	0.42	0.07	1.50	1.96
Mg	1.14	1.00	0.59	0.80	3.10	3.09
Na	2.21	1.50	1.86	0.70	7.40	1.93
Fe	0.12	0.06	0.18	0.02	0.74	3.04
pH	6.16	6.22	0.53	5.27	7.30	0.27
			Spring Lake			
Ca	5.02	4.33	2.15	1.65	9.17	0.41
Cl	20.24	20.00	1.49	16.90	23.00	−0.64
$NO_2 + NO_3$–N	0.04	0.01	0.05	0.01	0.13	0.06
NH_4–N	0.04	0.02	0.03	0.01	0.11	1.06
Total N	0.70	0.73	0.25	0.23	1.13	−0.45
Total P	0.05	0.01	0.14	0.01	0.54	3.85
K	8.44	8.01	1.32	7.50	13.00	3.28
Mg	8.64	8.50	1.44	7.00	13.00	2.08
Na	8.11	7.70	1.46	7.01	13.00	2.98
Fe	0.12	0.06	0.18	0.02	0.74	3.04
pH	7.65	7.60	0.49	6.94	8.61	0.49

2002, respectively, remained within the mesotrophic classification, while Spring Lake with TSI of 25 and 26 in 1993 and 2002, respectively, remained in the oligotrophic category. Lake Lindsey (mesotrophic lake) would normally have moderate nutrient concentrations with moderate growth of algae and/or aquatic macrophytes and with clear water (visible depth of 2.4 to 3.9 m). An oligotrophic lake such as Spring Lake would normally have less abundance of aquatic macrophytes and algae, or both because nutrients are typically in short supply. Oligotrophic lakes tend to have water clarity greater than 3.9 m due to low amounts of free-floating algae in the water column.

Bystere Lake, which was at the upper end of the mesotrophic range in 1993 (TSI of 49), shifted into the slightly eutrophic state in 2002 with a TSI value slightly above 50. Eutrophic lakes normally have green, cloudy water, indicating lots of algal growth in the water. Water clarity of most eutrophic lakes generally ranges from 0.9 to 2.4 m. Generally, water quality in Lake Lindsey and Spring Lake was consistently good (1993–2002) while water quality of Bystere Lake ranged from good in 1993 to fair in 2002 (Fig. 8).

CONCLUSIONS

Reduction of P transport to receiving water bodies is the primary focus of several studies because P has been found to be the limiting nutrient for eutrophication in many Florida aquatic systems (Botcher et al., 1998;

Table 6. Concentrations (mean ± SD) of nutrients in 1993 and 2002 in lakes associated with forage-based beef cattle operations.

Water quality parameter	Bystere Lake 1993	Bystere Lake 2002	Lake Lindsey 1993	Lake Lindsey 2002	Spring Lake 1993	Spring Lake 2002
	mg L^{-1}					
$NO_2 + NO_3$–N	0.10 ± 0.00	0.01 ± 0.00	0.10 ± 0.00	0.01 ± 0.00	0.10 ± 0.00	0.01 ± 0.00
NH_4–N	0.07 ± 0.01	0.03 ± 0.01	0.04 ± 0.04	0.19 ± 0.02	0.06 ± 0.04	0.03 ± 0.01
Total N	1.12 ± 0.58	0.76 ± 0.00	0.82 ± 0.24	0.80 ± 0.02	0.65 ± 0.19	0.78 ± 0.04
Total P	0.08 ± 0.01	0.34 ± 0.00	0.02 ± 0.01	0.02 ± 0.01	0.19 ± 0.30	0.01 ± 0.01
K	5.30 ± 0.14	7.65 ± 0.30	0.09 ± 0.02	1.02 ± 0.04	8.44 ± 0.45	8.00 ± 1.51
Ca	37.00 ± 2.83	43.00 ± 2.12	4.20 ± 0.26	2.59 ± 0.25	11.33 ± 0.58	17.76 ± 2.60
Na	5.35 ± 0.07	6.23 ± 1.54	1.40 ± 0.26	4.61 ± 0.55	8.59 ± 1.89	7.11 ± 2.25
Fe	0.04 ± 0.01	0.19 ± 0.10	0.04 ± 0.02	0.03 ± 0.00	0.005 ± 0.002	0.03 ± 0.00

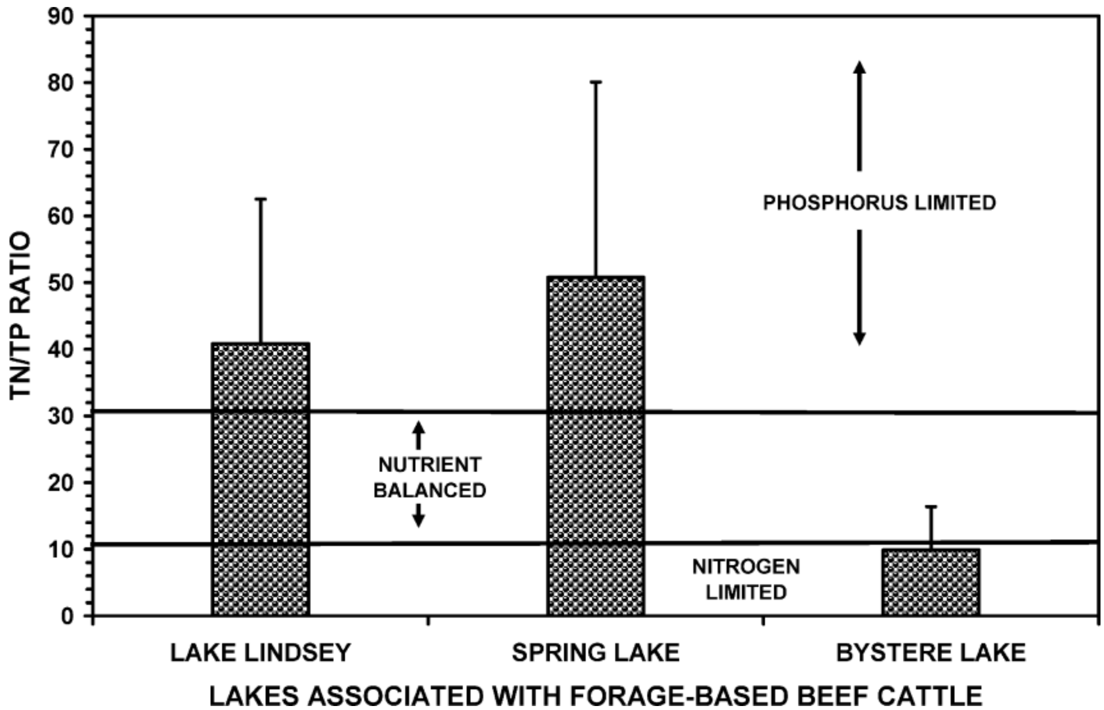


Fig. 7. Total nitrogen (TN) to total phosphorus (TP) ratio of lakes associated with a forage-based beef cattle pasture system.

Sigua et al., 2000; Sigua and Steward, 2000; Sigua and Tweedale, 2003). As a consequence, the way pasture management and hydrology interact to affect nutrient dynamics and water quality is an issue of increasing importance to environmentalists, ranchers, and public officials. Long-term monitoring of the changes in soil nutrients, especially soil P, would enable us to predict soil chemical or physical deterioration that could occur under continuous forage-livestock cultivation and to adopt measures to correct them before they actually happen.

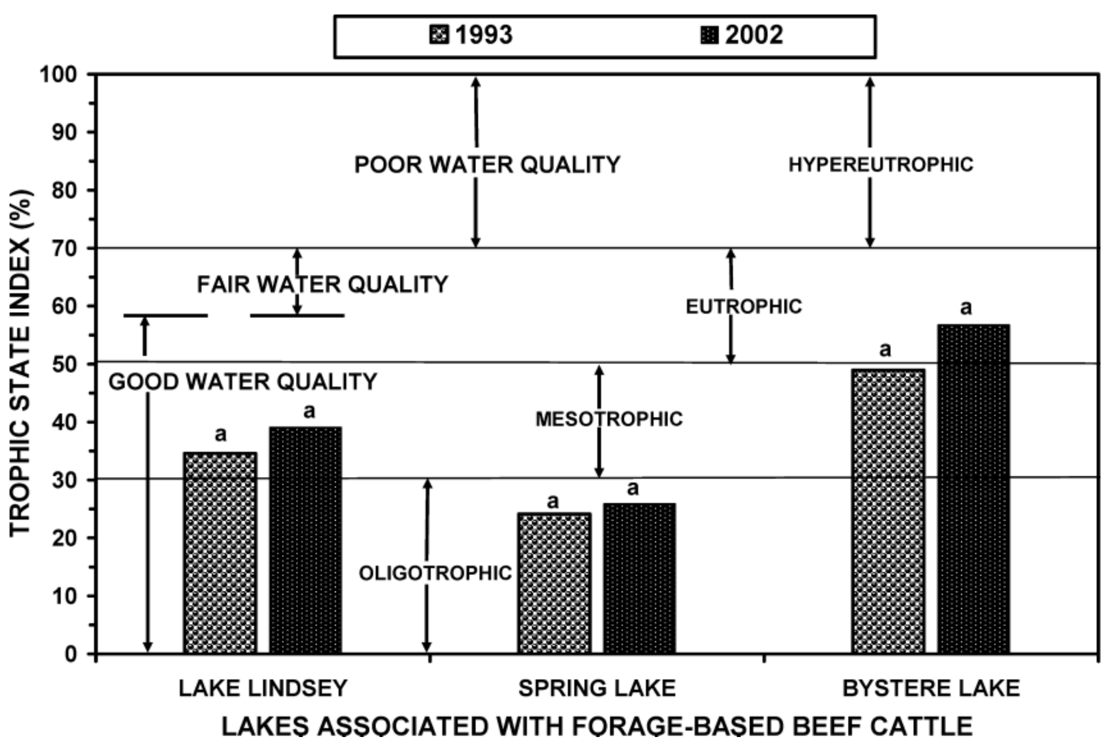


Fig. 8. Trophic state index for lakes associated with a forage-based beef cattle pasture system. Trophic state index is significantly different ($P \leq 0.05$) when superscripts located at top bars are different.

Water quality in lakes associated with cattle production was "good" (30–46 TSI) based on the Florida Water Quality Standard.

Soil testing programs should continue to measure the amount of soil nutrients that are proportional to what are available to RP-based pastures and continue looking at alternative soil nutrient tests that are better predictors of the loss and/or buildup of total and dissolved nutrients in water systems.

Our results indicate that current fertilization recommendations for RP-based pastures in central Florida offer little potential for negatively impacting the environment, and that properly managed livestock operations based on RP-based beef cattle pastures contribute negligible loads of nutrients (especially P) to surface water. In fact, our results suggest that current recommendations for P may be too low to adequately maintain RP growth. Periodic applications of additional P and other micronutrients may be necessary to sustain agronomic needs and to offset the export of nutrients due to animal production.

A major research area that relates to the pathways and rates of movement of nutrients deposited in urine and dung through various pools and back to the plants where knowledge is lacking would be the focal point of our future investigations (see Fig. 6). An understanding of these pathways is important because losses of nutrients will be decreased, hence fertilizer requirements and environmental pollution will be reduced.

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